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Abstract

FRP-confined concrete-encased cross-shaped steel columns (FCCSCs) are a new form of hybrid columns recently developed at the University of Wollongong. An FCCSC consists of a square FRP outer tube, a cross-shaped steel section and concrete filled in between. This sectional configuration ensures that the concrete is very effectively confined despite the square shape of the column, and that the steel section is well protected and constrained by the FRP tube from corrosion and buckling, leading to a column that is highly ductile and corrosion-resistant. In this paper, results from a series of stub column tests are presented to demonstrate some of the expected advantages of the new column form.

Keywords

columns; steel, cross-shaped, concrete-encased, frp-confined, column, tests, stub

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FRP-CONFINED CONCRETE-ENCASED CROSS-SHAPED STEEL COLUMNS: STUB COLUMN TESTS

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ABSTRACT

FRP-confined concrete-encased cross-shaped steel columns (FCCSCs) are a new form of hybrid columns recently developed at the University of Wollongong. An FCCSC consists of a square FRP outer tube, a cross-shaped steel section and concrete filled in between. This sectional configuration ensures that the concrete is very effectively confined despite the square shape of the column, and that the steel section is well protected and constrained by the FRP tube from corrosion and buckling, leading to a column that is highly ductile and corrosion-resistant. In this paper, results from a series of stub column tests are presented to demonstrate some of the expected advantages of the new column form.

KEYWORDS

FRP, steel section, concrete, tubular column, confinement.

INTRODUCTION

In the past two decades, fiber-reinforced polymer (FRP) has become increasingly popular as a confining material for both the strengthening of existing reinforced concrete columns (Teng et al. 2002) and for new construction (Teng et al. 2007; Yu et al. 2016a). As a result, extensive research has been conducted on the behavior of FRP-confined concrete (e.g. Fam and Rizkalla 2001; Teng et al. 2007; Yu et al. 2010). Existing studies have revealed that the FRP confinement is much more effective in circular columns than in square columns (Teng et al. 2002; Yu et al. 2013).

Against this background, a new form of hybrid columns incorporating an FRP confining tube has recently been developed at the University of Wollongong. The new form of columns is termed FRP-confined concrete-encased cross-shaped steel columns (FCCSCs). An FCCSC consists of a square FRP outer tube, a cross-shaped steel section and concrete filled in between (Figure 1). The square FRP tube typically has four rounded corners and contains fibers close to the hoop direction, while the width of the four flanges of the steel section is typically slightly smaller than that of the four flat sides of the FRP tube. In FCCSCs, the concrete is very effectively confined despite the square shape of the column: the cross-shaped steel section consists of two pairs of flanges connected by webs, so its confinement to the lateral expansion of the concrete infill depends on not only the flexural stiffness of the flanges, but also the axial stiffness of the web; this additional confinement is particularly important to the regions that are otherwise not effectively confined by the square FRP tube (i.e. the regions close to the four flat sides). In addition, the cross-shaped steel section serves as ductile longitudinal reinforcement needed for columns, in particular for those that are subjected to comparable loads in two lateral directions. The FRP tube protects the steel section from environment attacks and constrains its possible buckling, so a layer of concrete cover between the FRP tube and the steel flanges is not always needed. Nevertheless, in the cases where a thin steel section is used, such concrete cover may be provided to reduce the thickness of FRP tube needed for ductile response of the column. FCCSCs can be seen as a variation of concrete-filled FRP tubes with an embedded steel I-section (Karimi et al. 2011; Zakaib and Fam 2012; Yu et al. 2016b).

To demonstrate the concept of FCCSCs, results from two FCCSC specimens tested at the University of Wollongong are presented in this paper. For comparison, results of two square FRP-confined plain concrete (FCPC) columns tested in parallel with the FCCSC specimens are also presented.

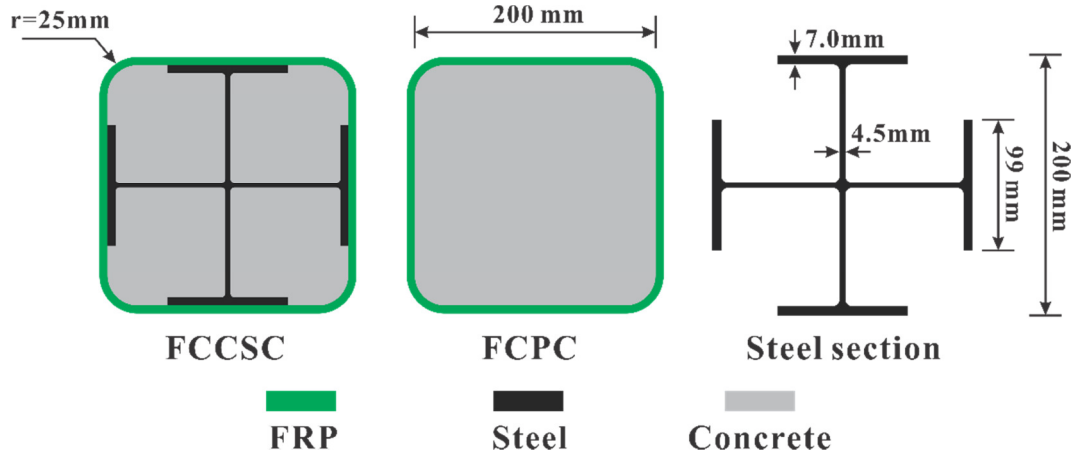


Figure 1. Cross-section of FCCSCs

TEST SPECIMENS

The test specimens included two nominally identical FCCSC specimens and two nominally identical FCPC specimens. The specimens all had a nominal width of 200 mm (width of the concrete core) and a height of 600 mm. The FRP tubes were fabricated via a wet-layup process by wrapping resin-impregnated glass fiber sheets around a foam core, with an overlapping length of 150 mm; the overlapping zone was limited within one side of the tube. The FRP tubes all had rounded corners with a radius of 25 mm, and were all composed of three plies of FRP. The cross-shaped steel sections were fabricated by welding two H-sections together (i.e. one was cut into to two T-shaped sections before welding to the other), and their dimensions are also shown in Figure 1. When preparing for the specimens, the prefabricated FRP tubes were used as the mould for casting concrete; for each FCCSC specimen, a cross-shaped steel section was put into the square FRP tube, which was fixed to a wooden frame, before casting concrete.

All specimens were cast in one batch using ready-mix concrete from a local manufacturer. Results from standard concrete cylinder (150 mm x 300 mm) tests showed that the compressive strength and compressive strain at peak stress of the concrete were 35.1 MPa and 0.0026 respectively. For the steel sections, tensile tests of steel coupons showed that the elastic modulus, yield stress and tensile strength are 216.6 GPa, 359.8 MPa and 516.5 MPa, respectively. In addition, an axial compression test was conducted on a steel section, which was identical to those in the FCCSC specimens, and the results showed that its ultimate load was 1662.5 kN. For the FRP tubes, tensile tests on FRP coupons showed that the FRP used in the present study had an average elastic modulus of 74.0 GPa based on a nominal thickness of 0.174 per ply.

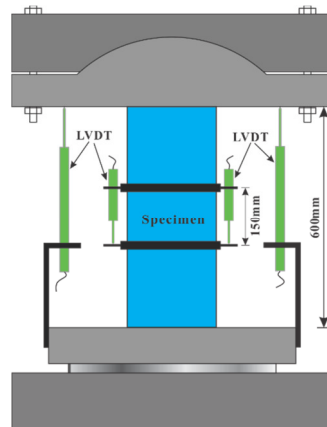


Figure 2. Test set-up

TEST SET-UP AND INSTRUMENTATION

For each specimen, two linear variable displacement transducers (LVDTs) placed 180° apart from each other were used to measure the overall axial shortening, while another two LVDTs placed 180° apart from each other

were used to measure the axial deformation of the 150 mm mid-height region. The layout of these LVDTs and the test set-up are shown in Figure 2. In addition, for each specimen, five (for FCPC specimens) or seven (for FCCSC specimens) hoop strain gauges with a gauge length of 20 mm were used to measure the hoop strain distributions at the mid-height of the specimens. All the compression tests were conducted at the University of Wollongong using a 500 ton Denison Compression Testing Machine with a displacement control rate of 0.6 mm per minute.

TEST RESULTS AND DISCUSSIONS

Failure Modes

All the specimens, including g FCCSC specimens and FCPC specimens, failed by the rupture of FRP tube under hoop tension, but the location of FRP rupture was somewhat different for the two types of specimens. Figure 3 shows the four specimens after tests. Figures 3a and 3b shows that the rupture of FRP tube in FCCSC specimens was close to the mid-height of the specimens; the FRP rupture was found to be distributed in both the corner regions and the flat sides (Figure 3b). By contrast, the rupture of FRP tube in FCPC specimens occurred within one of the flat sides close to the top of the columns (Figures 3c and 3d).

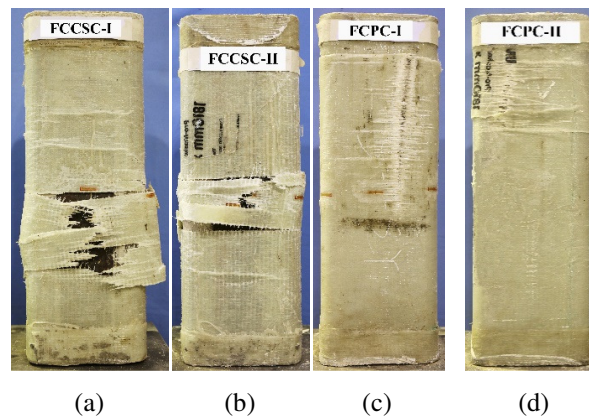


Figure 3. Specimens after test: (a) FCPC-I; (b) FCPC-II; (c) FCCSC-I; (d) FCCSC-II.

Axial Load-Shortening Behavior

The axial load-shortening curves of the four specimens are shown in Figure 4, where all the curves are terminated at the point of FRP rupture. Figure 4 shows that the curves of the two FCPC specimens both have a descend branch after the peak load, although the load decrease was generally gradual before the rupture of FRP tube. By contrast, the curves of the two FCCSC specimens feature a bilinear shape, consisting of two ascending branches. This difference was due to the existence of a cross-shaped steel section in FCCSC specimens, which not only contributed directly to the axial load capacity of the columns, but also provided additional confinement to the concrete.

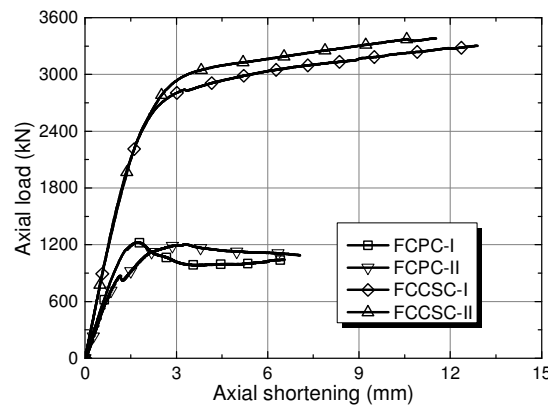


Figure 4. Axial load-shortening curves

The key test results are summarized in Table 1. In this table, P_u is the ultimate load of the FCPC or FCCSC specimens from the test; S_u is the ultimate axial shortening of the FCPC or FCCSC specimens from the test,

which is the shortening at the rupture of the FRP tube; P_c is equal to the peak average stress of confined concrete in the FCPC specimens times the net area of the concrete in FCCSC specimens; P_s is ultimate load from the compression test of steel section only; (P_c+P_s) represents the ultimate load of the specimen if the steel section did not interact with the concrete and the FRP tube in FCCSC specimens. It is evident from Table 1 that the ultimate loads P_u of FCCSC specimens are significantly higher than the (P_c+P_s) value, indicating that the strength of concrete in the FCCSCs were significantly enhanced by the additional confinement from the cross-shaped steel section. It is also evident that the ultimate shortenings of the FCCSC specimens are significantly higher than those of the two FCPC specimens. This is believed to be due to the following two reasons: (1) the steel section provided additional confinement to the lateral expansion of concrete, so that at the same axial strain, the hoop strain of FRP tube was smaller in FCCSC specimens than in FCPC specimens; (2) the existence of steel section reduced non-uniformity of lateral expansion of concrete, so that the average rupture strains of FRP tube was larger in FCCSC specimens than in FCPC specimens.

Table 1. Key test results

Specimen	Ultimate load P_u (kN)	Average P_u (kN)	Average $P_u/(P_c+P_s)$	Ultimate shortening S_u (mm)	Average S_u (mm)
FCCSC-I	3302.5	3342.6	1.22	12.90	12.22
FCCSC-II	3382.8			11.54	
FCPC-I	1224.1	1213.9	N/A	6.55	6.81
FCPC-II	1203.8			7.06	

CONCLUSIONS

This paper has presented a newly proposed hybrid column with a square FRP confining tube (i.e. FCCSCs). The new column consists of a square FRP outer tube and a cross-shaped steel section, with the space between filled with concrete. This sectional configuration ensures that the concrete is very effectively confined despite the square shape of the column, leading to a column that is highly ductile. This paper has also presented results from axial compression tests on stub columns to demonstrate the concept of FCCSCs. The results confirmed the excellent performance of FCCSCs. Compared with the concrete in FCPCs, the concrete in FCCSCs has a much larger ultimate axial shortening and a larger compressive strength, when the same FRP tube is used.

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